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Generation of an internally circulating mode in high-power superluminescent diodes with a grazing-stripe waveguide

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Received December 11, 2024
Revised January 28, 2025
Accepted January 31, 2025

The features of the occurrence of internally circulating modes in superluminescent diodes with a grazing-stripe waveguide with an active region based on 5 layers of InGaAs/GaAs quantum well-dots emitting in the range $1\,\mu$m are studied. A simple qualitative model is proposed that explains the decrease in the threshold current with an increase in the pump pulse duration. Approaches for suppressing internally circulating modes are proposed, which can significantly increase the output optical power of superluminescent diodes.

Keywords: quantum well-dots, optical waveguide, superluminescent diode, internally circulating mode.

DOI: 10.61011/0000000000

Superluminescent diodes (SLDs) constitute a special class of semiconductor emitters that are characterized by a wide emission spectrum (tens of nanometers) and a relatively high optical power [1]. In terms of output power, SLDs are closer to diode lasers; in terms of emission spectrum, they are more akin to LEDs. In the general case, the emission spectrum width is inversely proportional to the coherence length; therefore, typical SLDs have a small coherence length. This factor determines the key areas of application of SLDs: optical coherence tomography and fiber-optic gyroscopes [1]. SLDs are structurally similar to diode lasers: they have an active region that is integrated into an optical waveguide. The fundamental difference between SLDs and lasers is in the maximum suppression of positive feedback in SLDs. Owing to this, SLDs do not switch to lasing when population inversion is reached; instead, they operate in an amplified spontaneous emission mode (superluminescent mode). Their active regions are made of gain media similar to those used in lasers: quantum wells, quantum dots. Efficient feedback suppression is the main problem in SLD design. Theoretically, this may be achieved by introducing local losses, which suppress lasing, into an optical waveguide and/or by reducing reflectance at the facets of the waveguide. The latter approach is used in most practical cases. It may be implemented in several ways, such as through the application of antireflective coatings with a reflectance less than 10^{-5} to the output faces and/or the use of so-called tilted stripe waveguides. The latter method is relatively technologically simple, but the interference between incident and reflected light at the end of an inclined waveguide leads to the emergence of a resonant reflection spectrum, which is highly sensitive to the waveguide parameters (width, refraction index contrast) and to the SLD operation regime (temperature, pumping current). As a result, the optical gain may exceed losses and enable lasing at a certain pumping current. Residual Fabry-Perot modulation is another disadvantage of inclined stripes.

We have recently proposed a new simple stripe waveguide design that provides efficient feedback suppression in SLDs [2]. The key distinguishing element of this design is the use of a side facet of a superluminescent diode relative to which a stripe is inclined slightly; for this reason, the structure was called a grazing-stripe waveguide (Fig. 1, a). It was demonstrated that such SLDs with an active region based on InGaAs quantum well-dots allows one to reach a power level up to 150 mW with a spectrum width of more than 20 nm within a wavelength range of approximately $1\,\mu$m. It was noted that SLDs with a grazing stripe may support so-called internally circulating (IC) lasing modes. Modes of this type are known and have been studied in sufficient detail in high-power edge-emitting lasers, where they contribute to the breakdown of Fabry–Perot cavity lasing modes [3]. IC modes arise due to total internal reflection (Fig. 1, b) and may persist within the entire waveguide layer, including its active and passive regions. Since these modes have a high quality factor and low output optical losses, they are characterized by a narrow spectral line and a relatively low output intensity. In the case of a sufficient overlap with a high-gain medium, IC modes may be involved in lasing.

In the present study, we consider the features of emergence of internally circulating modes under pulsed and continuous-wave pumping, propose a qualitative model of the unusual dependence of the lasing threshold on pumping pulse duration, and discuss the options for suppression of these modes.

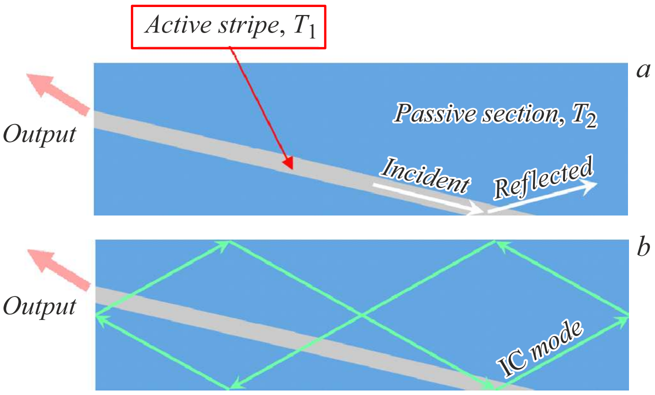

Figure 1. *a* — Schematic diagram of a superluminescent diode with a grazing-stripe waveguide. Active region temperature T_1 is higher than passive region temperature T_2. *b* — Diagram of formation of internally circulating (IC) modes in an SLD.

SLD samples similar to those studied in [2] were examined. The heterostructure was grown on a GaAs substrate by metalorganic vapor-phase epitaxy. Five layers of chirped InGaAs quantum well-dots with nominal emission wavelengths of 985, 1015, 1040, 1060, and 1075 nm were used as the active region. A specific wavelength was set for each active layer at the epitaxial growth stage by adjusting the nominal thickness of the deposited $In_{0.4}Ga_{0.6}As$ material (from four to eight monolayers). The active layers were separated by 40-nm-thick GaAs spacers. The active region was positioned at the center of the GaAs waveguide layer with a thickness of 0.44 μm sandwiched between $Al_{0.25}Ga_{0.75}As$ *n* and *p* emitters with a thickness of 1.5 and 1.2 μm, respectively. The thickness of the finishing GaAs contact layer was 200 nm. The width of the stripe waveguide was 20 μm, and the angle of its inclination to the output facet was 10°. In the studied samples, the quality of facets obtained by cleavage was controlled via dark-field optical microscopy. The waveguide length varied within the range of 1–2 mm. The examined samples were soldered p-side down onto copper heat sinks. The output radiation power was measured using a calibrated integrating sphere with an embedded optical fiber that was connected to a spectrum analyzer. Three types of pumping current were used: continuous, quasi-continuous (pulse duration, 10, 20, 50, 100, and 250 μs; frequency, 1 kHz), and pulsed (350 ns, 3 kHz).

A typical dependence of the SLD emission spectrum on the pumping current amplitude is shown in Fig. 2. The FWHM of the spectrum is close to 20 nm, which is noticeably smaller than the width of 92 nm obtained earlier for low-power SLDs fabricated from the same structure [4]. In general, as the output power increases, the emission spectrum of all types of SLDs tends to become narrower [5]. The SLD lasing threshold was determined as the point of emergence of a narrow line in the spectrum (Fig. 2). No kinks (or other features) in the emission–current dependence were observed at the threshold current (Fig. 3). An increase in duration of the pumping current pulse leads to a certain reduction in differential quantum efficiency, which is attributable to heating of the active region. This trend is typical for both LEDs and diode lasers. In the latter devices, an increase in pulse duration or temperature leads to an increase in threshold current, since the optical gain decreases due to thermal ejection of carriers from the active region. A different dependence is observed in the examined SLDs. The lasing threshold current under pumping with short pulses is several times greater than the one corresponding to CW pumping (Fig. 4). The threshold decreases as the pumping pulse extends to 100 μs; as the pulse duration increases further to the CW level, the threshold remains virtually unchanged.

The following qualitative model provides an explanation of this dependence. The key feature of lasing in the studied SLDs is that it is supported by internally circulating modes instead of Fabry–Perot ones. They form and propagate within the entire waveguide layer. An IC mode within the waveguide layer undergoes amplification when its optical path crosses the stripe waveguide, but undergoes absorption when it propagates in the passive region outside the stripe. The condition of equality between modal gain and the sum of all optical losses is the lasing condition. In the case of IC modes, the output losses may be neglected; therefore, the lasing threshold is specified by the dependence of modal losses in the passive region on pumping pulse duration.

In the general case, the pumping current causes local heating of the gain region located directly under the stripe contact, which translates into a difference between temperatures T_1 and T_2 of the gain and absorption regions, respectively (Fig. 1, *a*). With short pulses, the temperature difference is negligible and has no significant effect on optical modes. An increase in duration of pumping current pulses contributes naturally to the spatial temperature gradient, and the gain spectrum shifts toward longer wavelengths relative to the absorption spectrum of the passive region. This is confirmed by the observed red-shift of the lasing wavelength (Fig. 4). Note that this dependence cannot be used to estimate the change in temperature of the active region, since different IC modes may be involved in lasing at different pumping pulse durations. In the studied SLDs, modal optical losses for IC modes are reduced due to this effect, and the lasing condition under pumping with longer pulses is satisfied at lower current amplitudes. This feature of optical mode formation was examined in detail in high-power edge-emitting diode lasers [3] when the causes of breakdown of Fabry–Perot cavity mode lasing were investigated.

The formation of internally circulating modes in SLDs with a grazing-stripe waveguide requires further study, which should include numerical modeling. However, the already available data allow us to assess the options for suppressing these modes. Antireflective coatings on crystal faces or enhanced scattering are unlikely to induce a significant suppression of IC modes. Such modes have been observed even in sawn-cavity lasers [6]. It appears that they

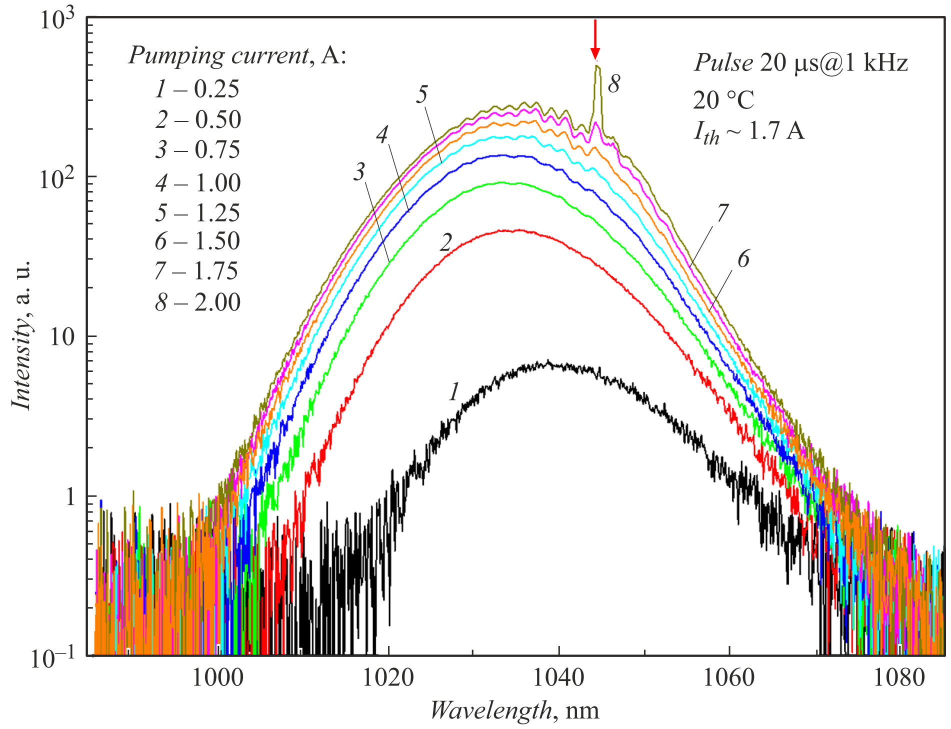

Figure 2. Evolution of the emission spectrum of the SLD with a waveguide length of 1.4 mm with a change in pumping current amplitude. The lasing line is indicated with an arrow. Lasing threshold I_{th} is close to 1.7 A.

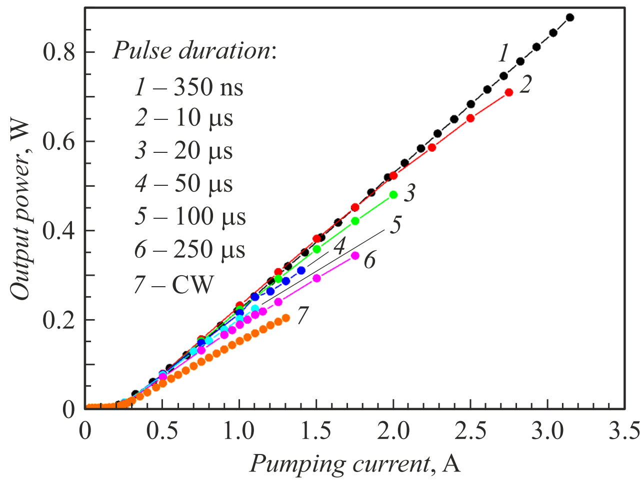

Figure 3. Emission–current dependences at different pumping current pulse durations and at continuous-wave (CW) pumping for the SLD with a waveguide length of 1.4 mm.

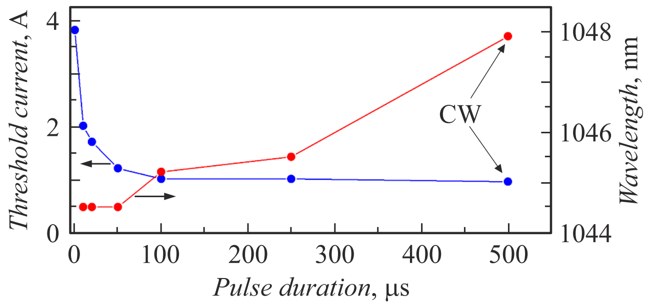

Figure 4. Dependence of the lasing threshold current and the lasing wavelength on pumping pulse duration for the SLD with a waveguide length of 1.4 mm.

may be suppressed by increasing the modal absorption. The simplest option here is to increase the size of the passive section of a sample; however, the obtained experimental data suggest that the effectiveness of this approach may be limited. Another option is the establishment of galvanic separation between the active and passive regions and the application of reverse bias to the latter. Such a region will then act as an effective absorber. The disadvantage of this solution is the need to mount the devices either p-side up on heat sinks, which may hinder their operation under CW pumping, or p-side down on metallized boards with individual contact pads, which makes the process of SLD fabrication significantly more complex. V-grooves formed by etching through the waveguide in the passive region may be used to suppress IC modes. Another possible approach is to produce nonradiative recombination centers in the passive region, which introduce additional optical losses into it, via ion implantation [7]. This technology may be combined with post-growth processing of structures.

Thus, the specifics of emergence of internally circulating optical modes in superluminescent diodes with a grazing-stripe waveguide pumped by continuous, quasi-continuous, and pulsed current were studied. A simple qualitative model explaining the lowering of threshold current with an increase in pumping pulse duration was proposed. The spatial temperature gradient in the waveguide layer plane inside the crystal was taken into account in this model. Several possible ways to suppress internally circulating modes, which may have a significant beneficial effect on the output optical power, were proposed.

Acknowledgments

Experiments were carried out at the „Complex Optoelectronic Stand" unique scientific facility (National Research University „Higher School of Economics," St. Petersburg).

Funding

This study was supported by grant No. 23-72-00038 from the Russian Science Foundation (https://rscf.ru/project/23-72-00038/). O.I. Simchuk wishes to thank the Ministry of Science and Higher Education of the Russian Federation (project FSRM-2023-0010) for support of the study of facets of tests samples by dark-field microscopy.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin